Solving the Santa Claus Problem

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A Comparison of Various Concurrent Programming Techniques

What did we do?

- Implemented ‘The Santa Claus Problem’ in a number of different programming paradigms.

Why did we do that?

- Investigate a number of concurrent programming techniques in order to better understand issues related to
  - Readability
  - Writability
  - Reliability
  - Error Handling

How did we do it?

- Write code…
  - Consider
    - Readability/Writability
      - What adds/detracts to/from the readability/writabilit
      - How does error handling affect this
    - Reliability
      - How do we know it works
      - Model checking possibilities
  - Count lines and compare

The Santa Claus Problem

[Originally by John Trono]

- Santa Claus sleeps at the North Pole until awakened by either all of the nine reindeer, or b a group of three out of ten elves.
- If awakened by the group of reindeer, Santa harnesses them to a sleigh, delivers toys, and finally unharnesses the reindeer who then go on vacation.
- If awakened by a group of elves, Santa shows them into his office, consults with them on toy R&D, and finally shows them out so they can return to work constructing toys.

Additional Constraints

- A waiting group of reindeer must be served by Santa before a waiting group of elves.
- Since Santa's time is extremely valuable, marshaling the reindeer or elves into a group must not be done by Santa.

Correctness of a Solution

- **Message ordering**: ensuring that events happen in c
at the right time.
- **Priority**: ensuring that the group of Reindeer have priority over any Elf groups that may be waiting at the time.
- **Self-Organization**: Santa cannot marshal a group of Elves or Reindeer, these groups must organize amor themselves without help from a Santa thread or proce
- **Synchronization**: synchronization between various processes
- **The usual freedom from deadlock, livelock, and starvation**.

Example: Elf Message Orderir

1. Elf <id>: need to consult santa, :(
2. Santa: Ho-ho-ho ... some elves are here!
3. Santa: hello elf <id> ...
4. Elf <id>: about these toys ... ???
5. Santa: consulting with elves ....
6. Santa: OK, all done - thanks!
7. Elf <id>: OK ... we’ll build it, bye ... :(
8. Santa: goodbye elf <id> ...
9. Elf <id>: working, :)

[Note, Reindeer Messages can be interspersed between elf messages]

Example: Reindeer Message Orderi

1. Reindeer <id>: on holiday ... wish you were here, :)
2. Reindeer <id>: back from holiday ... ready for work, :
3. Santa: Ho-ho-ho ... the reindeer are back!
4. Santa: harnessing reindeer <id> ...
5. Santa: mush mush ...
6. Reindeer <id>: delivering toys ... la-di-da-di-da-di-da,
7. Santa: woah ... we're back home!
8. Reindeer: <id>: all toys delivered ... want a holiday, :(
9. Santa: un-harnessing reindeer <id> ...

Process Requirements

- The following processes are required:
  - 10 elves
  - 9 reindeer
  - 1 Santa
- These processes might be needed for **synchronization** and **self-organization** reasons:
  - Processes to implement barriers
  - Processes to implement waiting rooms etc.

The Paradigms & Models

- Shared Memory (Threads)
  - Pthreads in C
  - Java and Groovy
  - .NET Threading library
  - Polyphonic C#
- Message Passing
  - MPI
- Process oriented
  - JCSP
  - Occam (Thanks to Peter Welch/Matt Pedersen)
  - Groovy (Thanks to Jon Kerridge)

And now for something …

- The next (many) slides will consider a number of issues dealing with
  - synchronization, priority, etc

  in the different programming models
  - What is the issue
  - How does it effect the code

C & pthreads

- Issue: Synchronization
  - For thread synchronization, we define our own barrier type using a mutex and a condition variable from the pthread library.
  - Santa code that uses the barriers:

```
    /* notify elves of "OK" message */
    AwaitBarrier(&elfBarrierTwo);
    /* wait for elves to say "ok we'll build
it" */
    AwaitBarrier(&elfBarrierThree);
```

C & pthreads

- Issue: Priority
  - Mutexes and Condition Variables used for Reindeer over Elves priority:

```
pthread_mutex_lock(&santaMutex);
pthread_cond_signal(&santaCondition);
pthread_mutex_unlock(&santaMutex);
```

  - A shared memory counter must be used to keep track of missed notifications.

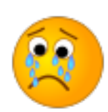
Java Threads

- Issue: Synchronization/Self organizati
  - Partial (and full) barrier
    - There are no barriers in the standard Java language
    - Solution: CyclicBarrier
      - CyclicBarrier [library in Java 1.5] for thread synchronization eliminates the need for explicit shared state among synchror threads
      - Re-entrant - call to `reset` will allow the barrier to be used ag

Java Threads

- Issue: Priority
  - Priority is achieved via `wait/notify`.
- The `notify` method is asynchronous, it will complete even if a Thread with a correspondi `wait` call is not currently ready to receive the notification:

```
synchronized (m_santaLock) {
  m_santaLock.notify();
  notifiedCount++;
}
```



[corresponding code exists on the Santa side]

Java Threads

- Issue: Spurious Wakeups.
  - Due to spurious wakeups, JVM is permitted to remove thread from wait sets without explicit instructions,which causes extra logic around calls to wait:

```
while (!<some condition>) {
   try {
        obj.wait();
    }
    catch(InterruptedException ie) { }
}
```

  - Where `<some condition>` is set by notifying thread.

.NET Thread library

- Issue: Synchronization
  - Very similar to mutex and condition variable programming with pthreads. We build our own Barrier type that can be used for synchronization around Monitors.
  - Same problem as Java threads and pthreads, the notification method, `Monitor.pulse`, is **asynchronous**, so threads must share state for the Santa thread to check for lost notifications

Polyphonic C# (Chords)

- Issue: Synchronization
  - Associates a code body with a set of method headers. The body of a chord can only run once all of the methods in the set have been called.

```
 int f(int n) & async g(int m) {
    …
}
```

  - A wait/notify mechanism that can prioritize notifications can be implemented with shared memory if chords are available to the programmer.

C & MPI

- Issue: Synchronization
  - Groups, or subsets of processes, can be formed at runtime, so we create a group that consists of Santa a all of the Reindeer:

```
MPI_Group_incl(groupWorld, TOTAL_REINDEER+1,
               santaReindeer, &groupSantaReindeer)

//create communicator based on subgroup
MPI_Comm_create(MPI_COMM_WORLD, groupSantaReindee
                &commSantaReindeer);
```

C & MPI

- Issue: Synchronization (continued)
  - MPI_Barrier:

```
// wait for all reindeer to say “delivering toys”
mpiReturnValue = MPI_Barrier(commSantaReindeer);
CHECK_MPI_ERROR(globalRank, mpiReturnValue);
printf("Santa: woah . . . we’re back home!\n");
```

  - Indirect synchronization using MPI_Send/MPI_Recv:

```
mpiReturnValue = MPI_Recv(&recv, 1, MPI_INT,
                          MPI_ANY_SOURCE,
                          elfTag, MPI_COMM_WORLD,
                         &status);
```

C & MPI

- Issue: Priority
  - Santa probes to see if the reindeer are ready before servicing a group of elves or reindeer with an asynchronous `MPI_Iprobe`:

```
int checkReindeerFlag = 0;
mpiReturnValue = MPI_Iprobe(REINDEER_QUEUE_PROC,
                            santaNotifyTag, MPI_COMM_WORLD
                            &checkReindeerFlag, &status);
```

  - We use separate processes to gather the deer or the 3 of 10 elves
    - REINDEER_QUEUE_PROC, ELF_QUEUE_PROC

JCSP

- Issue: Synchronization
  - Barriers with Channels (JCSP). Implemented barriers for synchronizing Santa and a group of 3 Elves or Santa and the Reindeer using 2 shared channels.
    - `MyBarrier` holds the reading end of the channels and `Sync` holds the writing end of the channels, only when all members of the barrier have sent their first message will a process start to send its second message to the reading end of the barrier:

```
// wait for Elves to say "about these toys"
new Sync(outSantaElvesA, outSantaElvesB).run();
outReport.write("Santa: consulting with Elves . . .\n");
```

JCSP

- Issue: Synchronization (Continued)
  - Santa and the Reindeer use an array of `One2OneChannelInt` types for synchronization.
    - Santa code:

```
//unharness a Reindeer
channelsSantaReindeer[id - 1].out().write(0);
```

    - Reindeer code:

```
//wait to be unharnessed
inFromSanta.read();
```

JCSP

- Issue: Priority
  - For priority, the JCSP version uses an alternation which waits for guarded events which can be prioritized:

```
final Guard[] altChans = { inFromReindeer, inKnock };
final Alternative alt = new Alternative(altChans);
switch (alt.priSelect()) {
  //...santa logic here
}
```

So Far … So Good

- We have seen examples of how to deal with
  - Synchronization
    - Full Barrier
    - Partial Barrier
  - Priority
  - Language Specific Curiosities
    - Lost notifications
    - Spurious wakeups

Readability/Writability Facto

- Readability and Writability are impacted by
  - Code to deal with undesirable concurrency behavior
    - Spurious wakeups, lost notifications
  - Code Coupling
    - Shared state
    - Message tagging
  - Error handling
    - More to come about that ….
  - Code to implement prioritized notifications
    - PriALT
    - MPI_Iprobe

Error Handling (Java)

- Checked exceptions in Java often require code that is quite verbose, even for simple logging of the exception. So a call to `CyclicBarrier.await()` looks like this:

```java
//notify elves of "OK" message
try {
  m_elfBarrierTwo.await();
}
catch (InterruptedException e) {
  e.printStackTrace();
}
catch (BrokenBarrierException e) {
  e.printStackTrace();
}
```

Error Handling (Groovy)

- Use **closures** for exception handling logic and thread related operations and a separate method takes the thread library call logic and wraps it in the exception handling logic:

```
//notify santa of "ok" message
performOperation(barrierAwait(m_elfBarrierThree))
```

Error Handling (C#/pthread

- Both the .NET threading library and the pthread library support errors, the languages do not force handling of the errors so the code is less verbose.
- In C# all exceptions are unchecked and the pthread library call return error codes which we (can) silently ignore.

Error Handling (MPI)

- The MPI library does not force error handling, but due to the distributed nature of MPI it is good practice to check for errors to MPI library calls. We define a macro `CHECK_MPI_ERROR` that will handle the errors

```
#define CHECK_MPI_ERROR(rank, errorId) { \
  if(errorId != MPI_SUCCESS) { \
    printf("Global Rank #%d exiting, mpi error code: %d\n",
                                                  rank, errorId);
    MPI_Finalize(); \
    return -1; \
  } \
}
```

[Note, Errors always imply termination, which can put the machine in an undesirabl state]

Error Handling (JCSP)

- The parts of the JCSP library that we used did not declare any checked exceptions, so there is no error handling code here.
- Occam/JCSP error handling on concurrency errors: poison

Error Handling (General)

- Seems that most error handling is language specific (`try/catch` etc)
- Concurrency errors often just terminates the program
  - Poison in process oriented language
  - Ctrl+c & “clean the virtual parallel machine” with MPI
  - Crash the program in Java/C etc.

Readability/Writability Resul

- Shared state increases coupling and makes re-factoring more challenging
- JVM spurious wakeups are nasty
- Java `Thread.notify`, pthread condition variable, and .NET `Monitor.pulse` may cause lost notifications, which forces shared state to be used among threads
- MPI synchronous receives are nicer for synchronizing than notify since the sent message does not get lost.

Readability/Writability Resul

- JCSP channels increase modularization and message integrity over MPI, must have explicit reading or writing end of a channel.

- Error handling is non-trivial in all cases.

Reliability

- Hard to reason about concurrent code.
- We could model check the code
  - CSP & FDR
  - SPIN
  - …

Model Checking

- JCSP/occam maps to CSP which can be model checked.
  - Might turn into machine assisted verification.
- MPI-Spin can be used to check various aspects of MPI.
  - Has less of a correspondence to MPI than CSP has to occam and JCSP

Line Count Comparison

	SM				DM	PO
	C#	C	Java	Groovy	MPI	JCSP
Total	642	420	564	315	352	315
Synchronization/Communication	48	49	46	46	34	27
Prevent Race Condition	14	8	8	8	N/A	N/A
Exception/Error Handling	35	0	177	18	41	0
Custom Barrier Implementation	42	35	N/A	N/A	N/A	55
GUI	145	N/A	N/A	N/A	N/A	N/A

SM = Shared Memory, DM = Distributed Memory, PO = Process Oriented

So what did we learn?

- Code that requires heavy synchronization can be done better ir MPI and even better in occam or JCSP than with threads.
- Prioritization is made easier with the prioritized alternation construct.
- Error handling is non-trivial in all cases.

More Santa

- Jon Kerridge's Groovy Fringe presentation
- Peter Welch's occam-π mobile processes Fringe presentation
- www.santaclausproblem.net for all the code

Future Work

- Different problems
- More models/languages, Shared Transactional Memory
- Feasibility/ease of model checking for the various models

Questions